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FURTHER EUVE OBSERVATIONS OF THE JUPITER SYSTEM

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Overview

The purpose of the grant to SwRI was to allow Dr. Gladstone to continue to:

- Assist in the reduction and analysis of relevant data (including observations of the Io torus, Io, and Jupiter) obtained by the *Extreme Ultraviolet Explorer (EUVE)* satellite.
- Compare modeled EUV emissions with *EUVE* data.
- Assist in the writing of articles for publication in scientific journals, and, as needed, in fulfilling prime award reporting requirements.

The rest of this report describes the progress made in each of these areas during the last year.

Data Reduction and Analysis

As in the previous years, the reduction of the *EUVE* data required a considerable amount of effort due to the nature of the target, Jupiter. Due to the proper motion of Jupiter over the 1994 and 1995 observations periods for *EUVE* observations, the position of the planet on the sky changed considerably (by about 40" per hour). The ability of *EUVE* to time-tag its photons allowed us to remap the photons after accounting for proper motion using an accurate ephemeris (using the JPL NAIF/SPICE package), and thus produce an undistorted spectral image of Jupiter at EUV wavelengths. All of the data have been saved in relatively compact form using IDL save files, and are available for direct comparison with similar data sets obtained in earlier and later years with *EUVE*.

Further Results During the Impact of Comet Shoemaker-Levy 9

The impact of comet Shoemaker-Levy 9 with Jupiter in July, 1994 was an event watched by nearly every available astronomical instrument, and the *EUVE* project devoted about 500,000 seconds of time to study this event. Dr. Gladstone was at CEA in Berkeley for two weeks (the impact week and the following week) and assisted in the planning and receipt of data in nearly real time, and performed quick-look analyses of the data. The major discovery of the experiment was that emissions at 58.4 nm from Jupiter were dramatically enhanced during the impacts.

During the past year, Dr. Doyle Hall presented the results of a careful analysis of the Io Plasma Torus EUV brightness during the impacts. No new spectral features were observed during the impacts, and the brightnesses of the known S and O emissions remained stable to within $\pm 20\%$.

Examination of the 1995 data shows that the Io Plasma Torus brightnesses are still within the normal range, although there is considerable variation in the dawn/dusk ansa brightness ratio.

Publication of Results

The results from the SL-9 impact observations by *EUVE* were written up by Dr. Gladstone in *Science*, and described in last year's report. Basically, this paper presents the observation of an enhanced He 58.4 nm signal from Jupiter during the week of the impacts, demonstrates that this brightening follows 2–4 hours after several of the larger fragment impacts, and postulates that the signal results from reflected solar 58.4 nm emissions from a temporarily-enhanced column of helium in Jupiter's upper atmosphere—the remnants of the impact-generated plumes.

The non-reaction of the Io Plasma Torus to the impacts at EUV wavelengths—it now appears that the EUV emissions from the torus remained essentially unchanged during the week of the impacts—has been published by Dr. Hall in *Geophysical Research Letters*. A reprint of this paper is attached.

Gladstone, G. R., D. T. Hall, and J. H. Waite, Jr., "EUVE Observations of Jupiter During the Impact of Comet Shoemaker-Levy 9," *Science*, **268**, 1595–1598, 1995.

Hall, D. T., G. R. Gladstone, F. Herbert, R. Lieu, and N. Thomas, "Io Torus EUV Emissions During the Comet Shoemaker-Levy/9 Impacts," *Geophys. Res. Lett.*, **22**, 3441–3444, 1995.

Io Torus EUV Emissions During the Comet Shoemaker-Levy/9 Impacts

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Abstract.

Extreme Ultraviolet Explorer satellite observations of Jupiter's Io plasma torus conducted over a two-year time period before, during and after the impacts of comet Shoemaker-Levy/9 reveal that no new spectral features appeared in the 400–715 Å spectral region. Io torus emission line luminosities remained stable to within $\pm 20\%$ and showed no strong coherent increasing or decreasing trend during the weeks preceding or following the impact events. This work supersedes our previous claims of possible luminosity changes to the torus derived from the same data (McGrath et al., *Science*, 267, 1313, 1995).

Introduction

We report Extreme Ultraviolet Explorer (EUVE) observations of Jupiter's Io plasma torus conducted before, during and after the arrival of the fragments of comet Shoemaker-Levy/9 (SL9) and associated dust clouds. We concentrate on luminosity variations of the entire torus in the 400–715 Å spectral range, and defer discussion of other aspects of the emissions, such as spatial structure, dawn-dusk asymmetries, and modulations with Jupiter longitude or Io orbital phase. (Enhanced HeI 584 Å emissions from Jupiter's upper atmosphere observed by EUVE during the impacts are discussed by Gladstone et al., [1995].) Previously, extreme-ultraviolet (EUV) emissions from the Io plasma torus have been observed by both Voyager spacecraft and the

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Hopkins Ultraviolet Telescope [Broadfoot et al., 1979; Moos et al., 1991]. Produced primarily by electron-impact excitation of oxygen and sulfur ions, the line emissions are diagnostic of the plasma density, relative ion partitioning, and the electron energy distribution [Shemansky and Smith, 1981].

During its first observation of the Jupiter system (1993 days 89–91) EUVE obtained a 60,000 second accumulated exposure that showed a rich emission-line spectrum from the Io torus spanning the wavelength range 370–735 Å [Hall et al., 1994a]. EUVE accumulated approximately ten times as much exposure time in 1994, distributed in observations before, during and after the arrival of the SL9 fragments and dust clouds.

EUVE Data Acquisition and Reduction

EUVE is a NASA explorer-class satellite launched in June 1992 into a 90-minute, 520 km circular orbit with a payload including three spectrographs covering the 70–750 Å spectral range (see Bowyer, [1994]). As discussed by Hall et al., [1994a], raw data from each spectrograph consists of a series of time-tagged photoevents that are filtered and accumulated to produce spectral images. The best time to observe Jupiter (or any target) with EUVE is when its position in the sky is closest to the anti-sun direction. This minimizes geocoronal HeI 584 Å and HeII 304 Å foreground emissions as well as absorption of target photons by atomic oxygen in Earth's upper atmosphere, because during orbital night-time (when EUVE observations are conducted) the line-of-sight passes above the Earth's limb at high altitudes. However, because of the relative Earth-Sun-Jupiter positions, observations during

the week that the comet fragments impacted Jupiter (1994 days 197–203, or July 16–22) were necessarily performed when the EUVE line-of-sight subtended relatively large angles ($\geq 80^\circ$) from the anti-sun direction. Follow-up measurements continued into August 1994 until Jupiter's anti-sun angle reached 103° and spacecraft operational constraints prevented further observations until March 1995. EUVE observations during July and August 1994 were affected by Earth atmosphere absorption because for an increasing fraction of each progressive spacecraft orbit, the line-of-sight passed within 200 km of Earth's surface, where absorption is known to be significant [Miller and Abbott, 1995]. Spectra presented here only include data acquired during periods when terrestrial atmosphere absorption was negligible. Earlier reductions of EUVE data [Hall et al. 1994b; McGrath et al. 1995] did not properly exclude data that were attenuated by atmospheric absorption, and the Io torus luminosities reported for July and August 1994 in these publications were erroneously low.

Io Torus EUV Spectra (400–715 Å)

Figure 1 shows eight EUVE long wavelength (LW) detector spectra of the Io plasma torus accumulated over various periods during 1994 and 1995. Because the projected orientation of the Io torus on the LW detector changed from observation to observation, each spectrum has a slightly different effective spectral resolution varying between 3 and 4 Å FWHM. Because the Earth-Jupiter distance, D , varied between 4.4 and 5.6 AU during the various observations, measured fluxes were multiplied by $4\pi D^2$ to convert to total emission luminosities. These data were reduced using the latest available revision of the LW detector effective area curve (EUVE reference data set *egodata1.10*, April 1995). Fluxes for the 1993 Jupiter observation reported by Hall et al., [1994a] were derived using an earlier, preliminary effective area curve and are generally smaller than those presented here by ≈ 20 –50%.

All emission features in Figure 1 correspond to known multiplets of sulfur and oxygen ions (see Hall et al., [1994a] for detailed spectroscopic identifications.). The brightest feature, SIII 680 Å, is excited by electron-impact of doubly-ionized sulfur, and the brightest feature shortward of 565 Å is the OII 539 Å multiplet. The week that the fragments of comet SL9 impacted Jupiter was 1994 days 197–203 (July 16–22), and as is evident in Figure 1, no statistically significant new spectral features appeared either during or following the impacts. By comparing the luminosity of the OII 539 Å multiplet with the $2\text{-}\sigma$ upper limit luminosities for the CII 687 Å and SIII 567 Å multiplets, we estimate that the number densities of C^+ and Si^{++} never exceeded 15 and 20% (respectively) of the O^+ number density during and after the impacts. Estimating upper limit abundances of other ions of cometary origin (e.g., Si^+) is also possi-

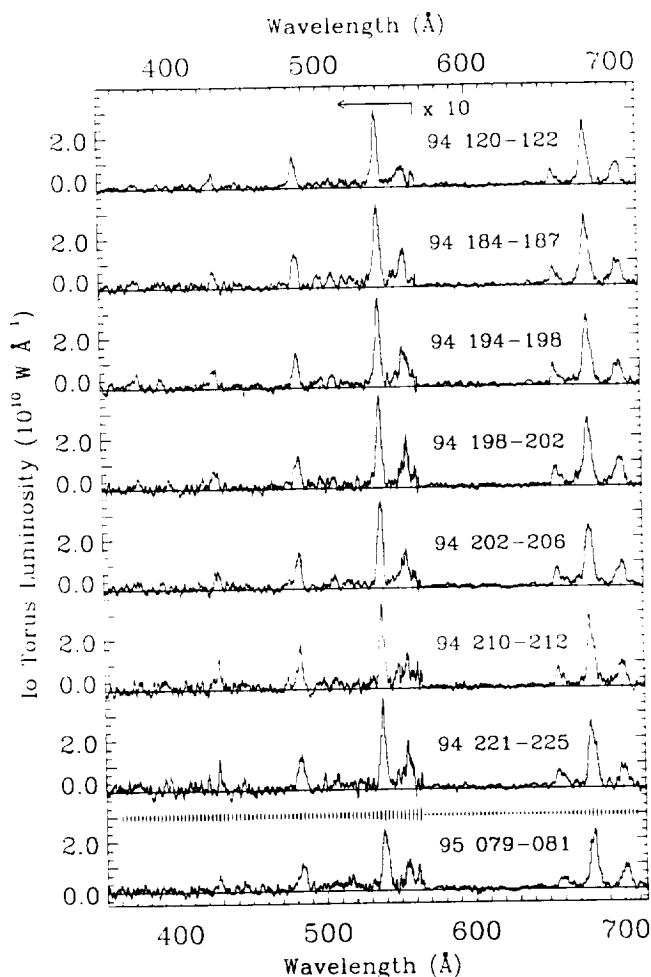


Figure 1. Io plasma torus spectra acquired by EUVE during various periods in 1994. These eight spectra show Io torus EUV luminosities in the 400–715 Å spectral range during the 1994 and 1995 day of year ranges indicated in each panel. For clarity, the spectra are smoothed over 5 pixels and are multiplied by 10 shortward of 565 Å. Each spectrum represents emissions from the entire torus (except the fraction naturally obscured by Jupiter) averaged over several Jupiter rotations. The series of vertical lines in the bottom panel shows representative $\pm 1\text{-}\sigma$ statistical measurement uncertainties. The emission line features are all known multiplets of sulfur and oxygen ions, and are produced by electron-impact excitation. The week that the fragments of comet SL9 impacted Jupiter was 1994 days 197–203; no statistically significant new spectral features appeared either during or following the impacts.

ble, but requires electron-impact emission rates that are currently unavailable.

Io Torus EUV Luminosity Variations

The top two panels of Figure 2 show the integrated luminosity from the entire Io torus as a function of time for the SIII 680 Å and OII 539 Å features respec-

tively (each data point represents the luminosity averaged over one complete Jupiter rotation). Before 1994 day 190 the observations were widely separated in time (note the axis breaks in Figure 2), and the luminosities appear roughly constant with $\pm 20\%$ variations. To monitor the arrival of the comet fragments, EUVE observed Jupiter as continuously as possible during 1994 days 193–206, and measured luminosities that were 10–20% larger than the average of all preceding observations. After 1994 day 206, the luminosities scatter about the mean value of preceding observations. The luminosity ratio of the 680 Å and 539 Å features (Figure 2, bottom panel) remained roughly constant throughout the entire two-year period. To within statistical uncertainty, this basic behavior is reproduced in the other EUV emissions as well.

The luminosity for the combined emissions in the 650–710 Å spectral range was $(2.5\text{--}3.0) \times 10^{11}$ W during the two-year observation period. Using an electron-impact excitation model developed to calculate Io torus ion emission rates [Shemansky *et al.* 1980; Shemansky and Smith 1981], and representative plasma parameters from Bagenal, [1994], we estimate that roughly 8–27% of the power radiated from the torus is emitted in the 650–710 Å interval. This implies that the total power emitted at all wavelengths during the two-year EUVE observation period was roughly $(1\text{--}4) \times 10^{12}$ W, comparable to estimates based on Voyager measurements [Sandel *et al.*, 1979; Shemansky and Smith, 1981].

Discussion

Previous discussions of Io torus observations during the SL9 impacts [Hall *et al.* 1994b; McGrath *et al.* 1995] incorrectly reported that EUV emission luminosities decreased by 30–50% during the impact period. This was because the EUVE data had not been filtered properly to exclude portions of each spacecraft orbit when Earth atmosphere absorption of Io torus photons was significant. Because the data affected most strongly were acquired during July and August 1994, the decreased luminosities coincidentally appeared to be associated with the arrival of the comet fragments and dust. The properly-filtered data indicate that, although there may be a slight enhancement of EUV luminosity during the weeks preceding and following the impacts, no strong and coherent upward or downward trends in luminosity were observed and no new spectral features were detected. Thus the EUVE Io torus measurements obtained during the impacts of comet SL9 are similar in character to observations at longer wavelengths, in that emission levels and morphology observed during the impact events were similar to those observed before the events [see McGrath *et al.*, 1995].

Despite the absence of strong changes in the Io torus, two significant magnetospheric effects were observed closer to the planet. Synchrotron radiation belt emis-

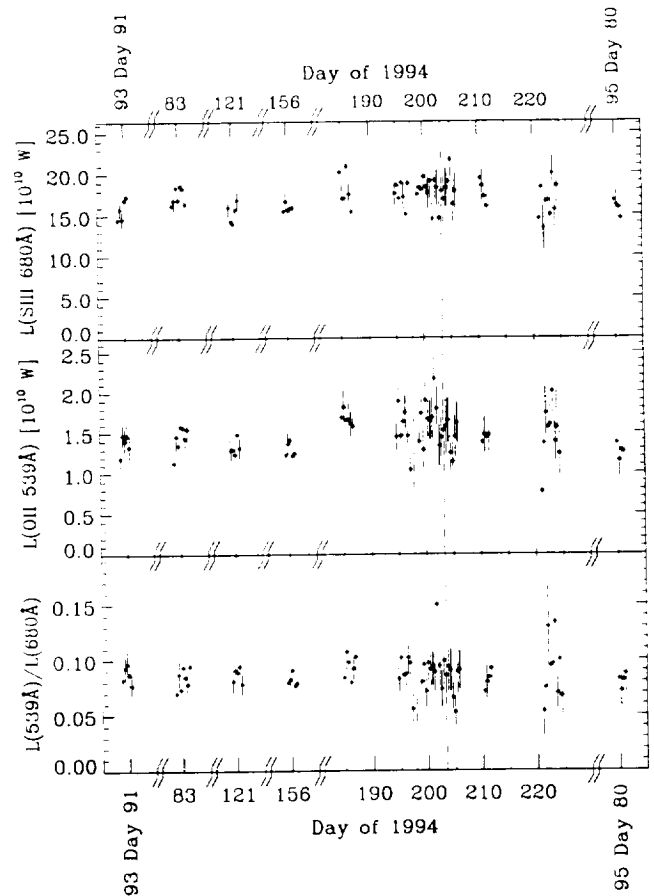


Figure 2. Io plasma luminosities observed over a two-year period for the SiII 680 Å spectral feature (top panel) and the OII 539 Å feature (middle panel). The time range spans all EUVE observations conducted through March 1995, and each data point represents the luminosity averaged over one Jupiter rotation (note the axis-breaks on the horizontal time axis.) The vertical dashed lines mark the times of the first and last comet SL9 fragment impacts on Jupiter. The bottom panel shows the ratio of the luminosities. Error bars show $\pm 1\text{-}\sigma$ statistical measurement uncertainties.

sions (near 2 Jupiter radii, R_J) increased during the impact week, followed by a gradual decline lasting several months [de Pater *et al.*, 1995]. Transient auroral emissions appeared just after the K fragment impact, but in Jupiter's northern hemisphere at locations nearly connected to the impact site by magnetic field lines that extend out to $\approx 2 R_J$ [Clarke *et al.*, 1995]. McGrath *et al.*, [1995] note that, although gas plumes and shock waves from the impacts naturally traversed magnetic field lines connected to the inner radiation belts, the absence of marked changes in the torus implies that a significant amount of material did not traverse field lines connected to the torus.

Herbert [1994] predicted that the arrival of comet SL9 could lead to a brightening of torus emissions because cometary gases ionized in Jupiter's outer magnetosphere would be heated by compression during inward

transport to the torus and, upon arrival, would raise the ambient effective electron temperature and brighten the EUV emissions. Even though EUVE observed a modest (10–20%) luminosity increase during the impact period that could be explained by a small (≤ 0.3 eV) enhancement in electron temperature, the timing of the brightening does not follow the prediction. From Figure 2, the luminosity increase began between 1994 days 156 and 185, at least 13 days before the first impact. We estimate that the dominant part of the mass of any extended cometary gas cloud could have begun to arrive in the outer magnetosphere at most a few weeks earlier than the first nucleus. Herbert [1994] estimated that, once ionized, transport of the hot plasma from the outer magnetosphere to the torus would require about two months, so the predicted brightening should have started a few weeks after the first impact, and ended a month or two later. Thus, either the plasma transport time used in the prediction was too short by a factor between 3 and 10, or, more likely, the comet outgassing rate was inadequate to produce a detectable level of brightening (i.e., the modest luminosity increase actually observed was not caused by the suggested mechanism). From Figure 1 of Herbert [1994] we deduce that if the combined fragment outgassing rate was greater than about 10^{25} molecules s^{-1} , the predicted brightening signature should have been detectable, even superimposed on the observed 10–20% luminosity variations.

Dessler and Hill [1994] predicted that the Io torus would be affected negligibly by the arrival the SL9 fragments and dust. This conclusion stemmed from the fact that, because of the unfavorable geometry of how each comet tail traversed the torus volume, the mass loading rate of comet material into the torus probably would never exceed a few percent of the $\sim 10^3$ $kg s^{-1}$ that Io is estimated to provide. Since EUVE and all other observatories having established baseline data show that Io torus emissions remained within nominal variational limits, it is reasonable to conclude that the Dessler and Hill [1994] prediction was correct.

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